

DEVELOPMENT AND APPLICATION OF HIGH TEMPERATURE SENSORS AND ELECTONICS

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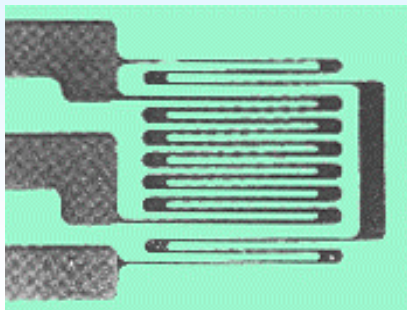


OUTLINE

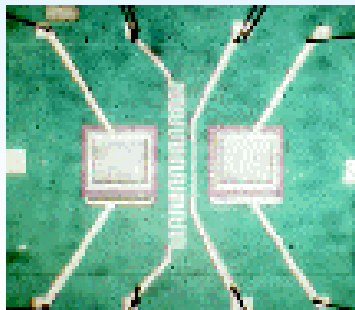
- **INTRODUCTION**
- **PHYSICAL SENSOR TECHNOLOGY**
 - THIN FILM SENSORS**
 - LEAD WIRES**
- **SiC HIGH TEMPERATURE ELECTRONICS/SENSORS**
 - PRESSURE SENSOR**
- **CHEMICAL SENSOR TECHNOLOGY**
 - TIN-OXIDE BASED GAS SENSORS**
 - HIGH TEMPERATURE ELECTRONIC NOSE**
- **SUMMARY/COMMON THEMES**

SENSORS & ELECTRONICS TECHNOLOGY BRANCH

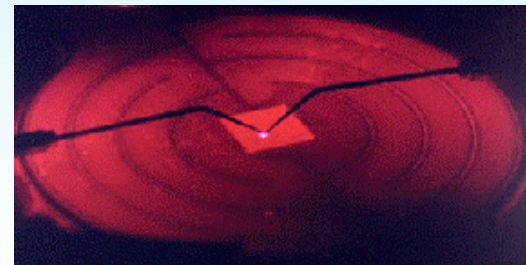
SCOPE OF WORK



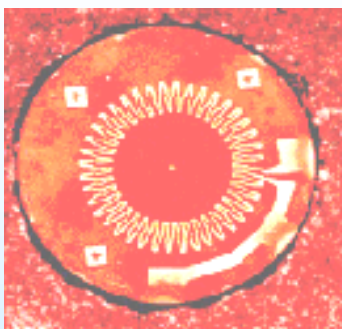
STRAIN GAGES



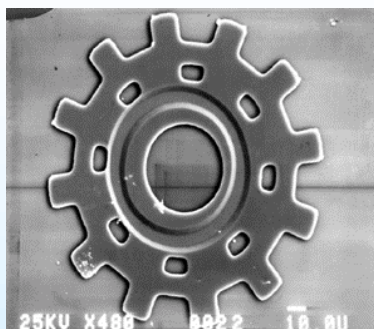
CHEMICAL SENSORS



**SILICON CARBIDE HIGH
TEMPERATURE ELECTRONICS**



HEAT FLUX GAGES



**MICROELECTROMECHANICAL
SYSTEMS (MEMS)**



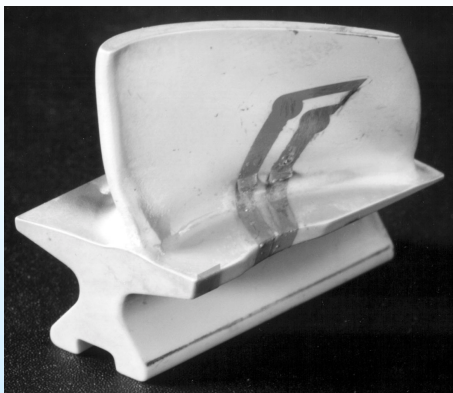
TEMPERATURE SENSORS



THIN FILM SENSOR TECHNOLOGY

- VERY THIN, MINIMALLY INTRUSIVE SENSORS ABLE TO PROVIDE HIGH TEMPERATURE DATA WITHOUT DISTURBING AIR FLOW
- CAN BE FABRICATED DIRECTLY ON CERAMIC AND METAL ENGINE PARTS WITHOUT THE NEED TO CUT INTO THE PART.
- CAN BE APPLIED TO METAL BASED MATERIALS, CERAMIC MATERIALS, AND CERAMIC MATRIX COMPOSITES.
- MULTIFUNCTIONAL, INFORMATION RICH SENSORS CURRENTLY UNDER DEVELOPMENT

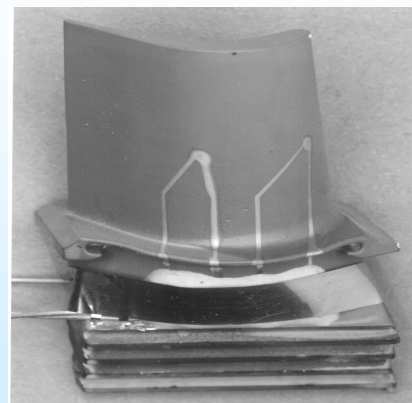
1995 R&D 100 Award



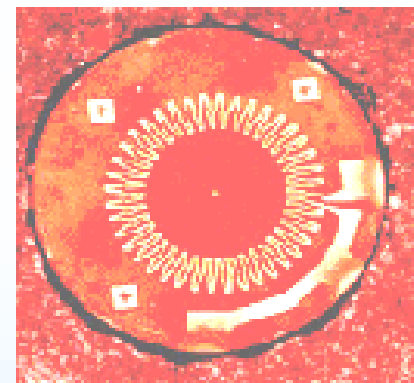
**PdCr THIN FILM GAUGE
APPLIED ON ALLIED-SIGNAL
ENGINES CERAMIC TURBINE
BLADE**



**THIN FILM THERMOCOUPLES
ON CERMIC MATRIX
COMPOSITE HOOP**



**THIN FILM
THERMOCOUPLES ON
SPACE SHUTTLE MAIN
ENGINE TURBINE BLADES**



**HEAT FLUX GAGE ON
SILICON NITRIDE PLUG**

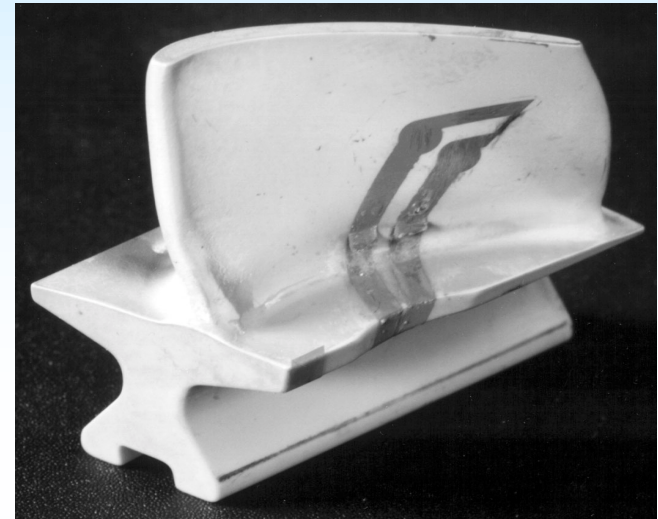
HIGH TEMPERATURE STRAIN SENSOR TECHNOLOGY

1991 R&D 100 Award



PdCr wire strain gauge applied on
Ford Motor Co. exhaust manifold

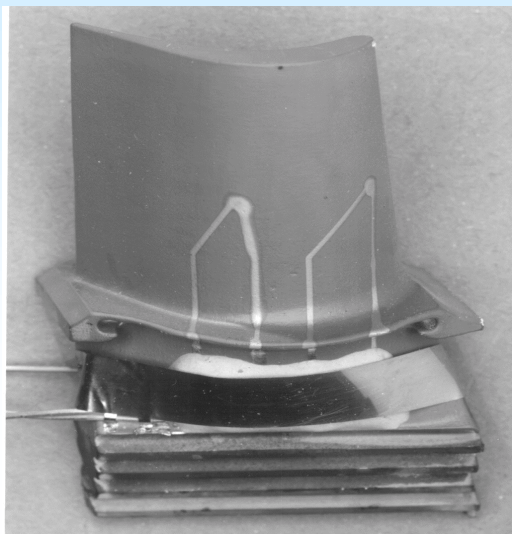
1995 R&D 100 Award



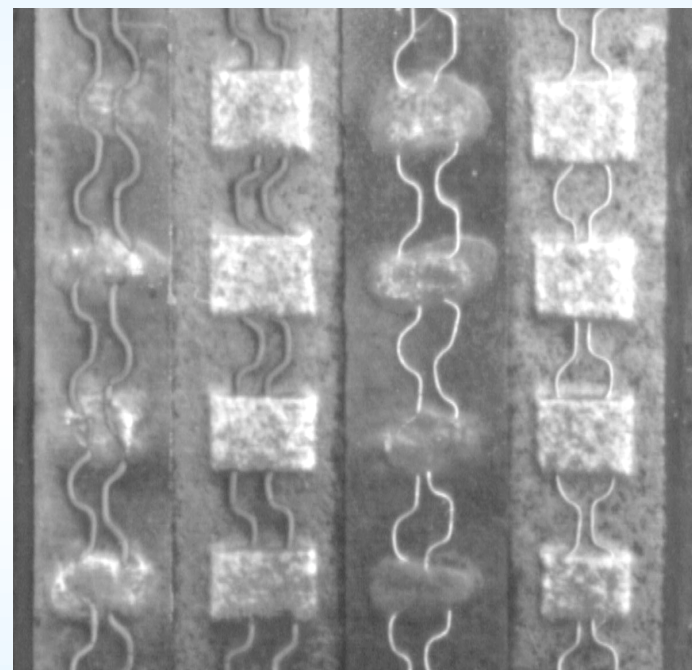
PdCr thin film gauge applied on Allied-
Signal Engines ceramic turbine blade

- High temperature strain sensors developed based on a newly developed alloy, PdCr.
- Wire gauge operates to 800 °C and thin film gauge operates to 1100 °C, compared to 400°C of the commercially available technologies.
- Technology transferred to Pratt & Whitney, GEAE, AlliedSignal Engine, Allison, Ford Motor et al. for advanced materials and engine testing.
- Wire strain gauge technology commercialized.
- New ceramic gauge materials being explored for higher temperature applications.

LEAD WIRE CONNECTIONS SIGNIFICANT PROBLEM



STANDARD APPROACH



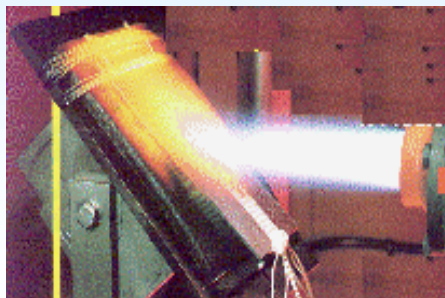
“CONVOLUTED” APPROACH



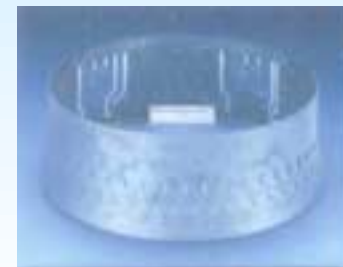
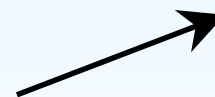
Long-lived Convoluted Thermocouples For Ceramics Temperature Measurements 1998 R&D 100 Award



Sensor configuration



Burner rig evaluation



**Applied to a GEAE IHPTET
SiC/SiC combustor liner**



Applied to a C/SiC cylinder

**Unique convoluted design and installation technique successfully
provided the needed thermal stress relief**

**Good adhesion on ceramic based materials such as ceramic
matrix composite**

**Operating in a hostile environment (1300 C 4560 torrs) for
a long period of time (>20 hrs)**

A better, faster, cheaper enabling technology

Commercialized by HiTec Products Inc.



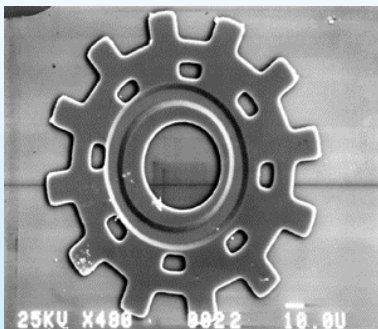
SiC-BASED MICROSYSTEMS

•SiC-based electronics and sensors can operate in hostile environments (600 C = 1112 F **GLOWING RED HOT!**) where conventional silicon-based electronics (limited to 350 C) cannot function.

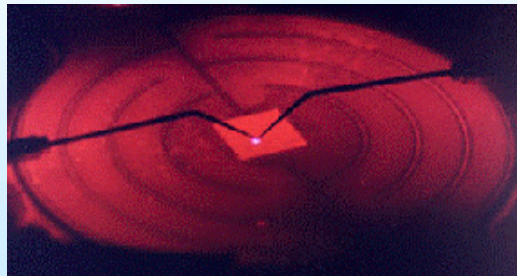
SiC-BASED MICROSYSTEM BENEFITS

- Operation in High Temperatures, High Power, High Radiation, and Harsh Environments
- Reduced Size, Weight, and Power Consumption- Electronics in Harsh Environments
- Use Si Based Processing Techniques

INTEGRATED SYSTEMS FOR USE IN HARSH ENVIRONMENTS



ACTUATORS



ELECTRONICS



SENSORS

SiC-BASED PRESSURE SENSORS

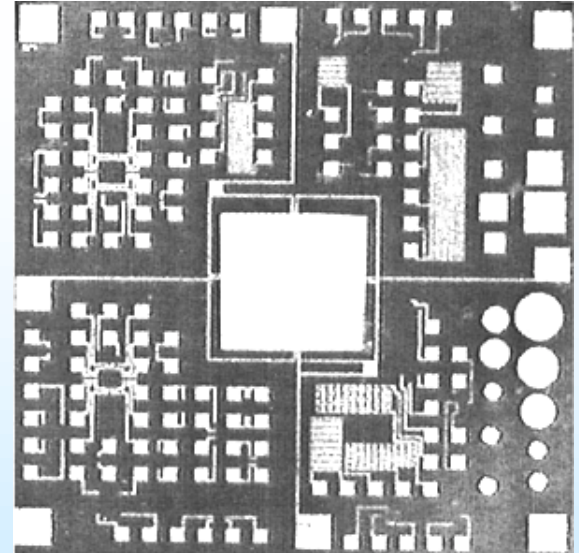
- **SiC HAS EXCELLENT MECHANICAL PROPERTIES FOR USE AS A HARSH ENVIRONMENT PRESSURE SENSOR ($T > 500\text{ }^{\circ}\text{C}$, SILICON UNDERGOES PLASTIC DEFORMATION)**

**STRONG MATERIAL
LARGE PIEZORESISTIVE COEFFICIENTS**

- **FORM DIAPHRAM OF SiC AND INTEGRATE WITH ELECTRONICS**
- **WIDE RANGE OF APPLICATIONS**

**AERONAUTIC ENGINE APPLICATIONS
AUTOMOTIVE APPLICATIONS
WIND TUNNELS
MATERIAL PROCESSING**

- **TWO APPROACHES
SiC DIAPHRAM ON Si
SiC DIAPHRAM ON SiC**

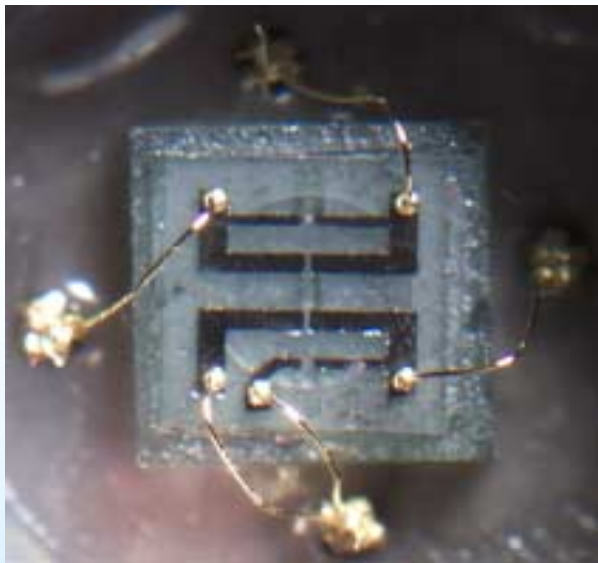


**SiC Pressure Sensor
with Electronics**

HIGH TEMPERATURE SiC PRESSURE SENSORS: KEY TECHNOLOGIES

Key technologies:

- SiC micromachining
- High temperature contacts
- High temperature packaging



SiC pressure sensor, magnified

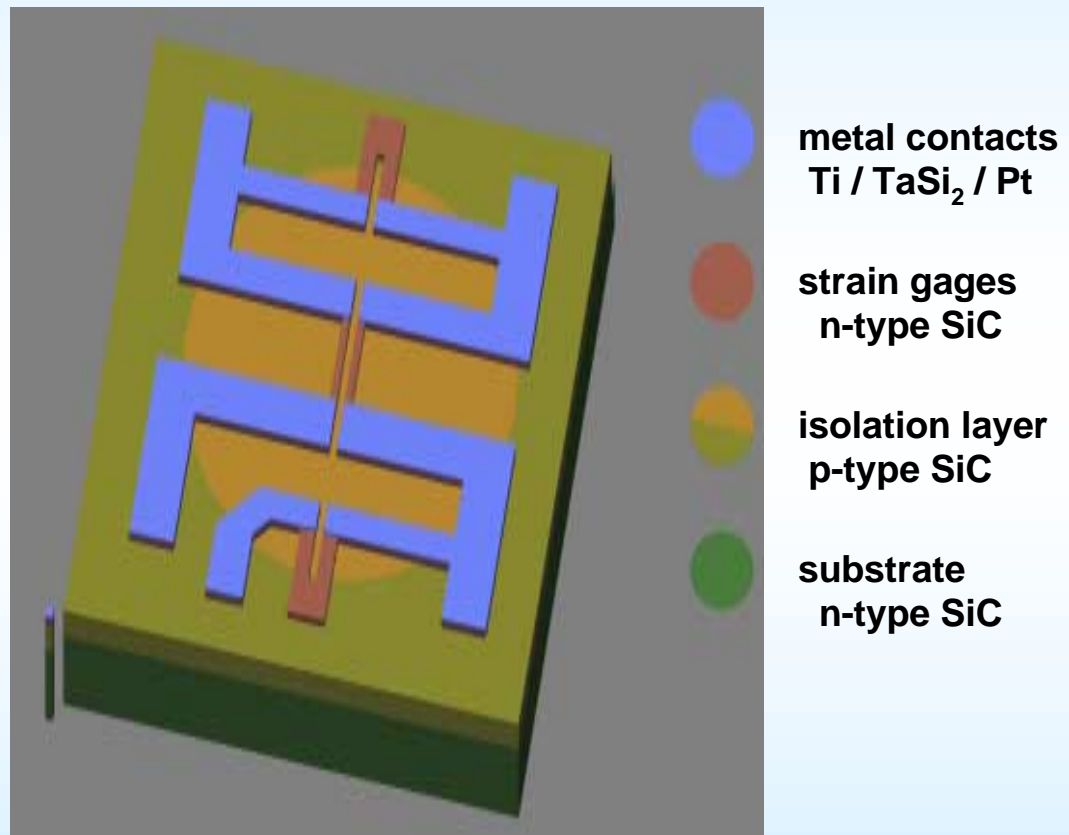


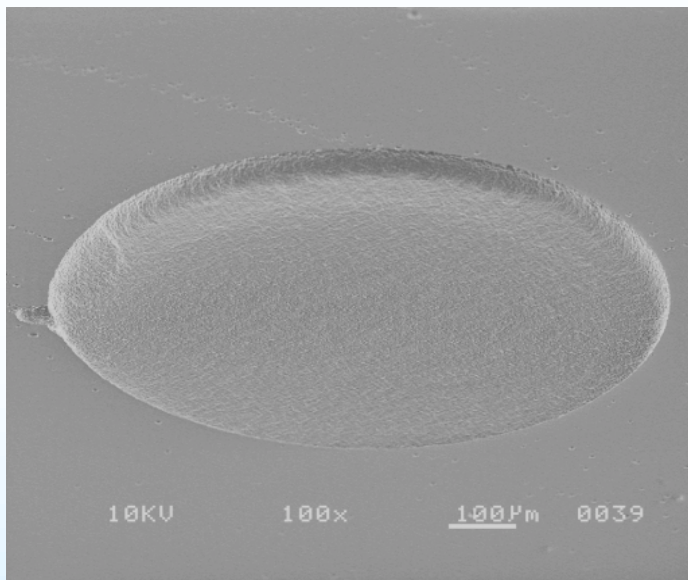
Diagram of SiC pressure sensor

TECHNOLOGY DEVELOPMENT: SiC MICROMACHINING

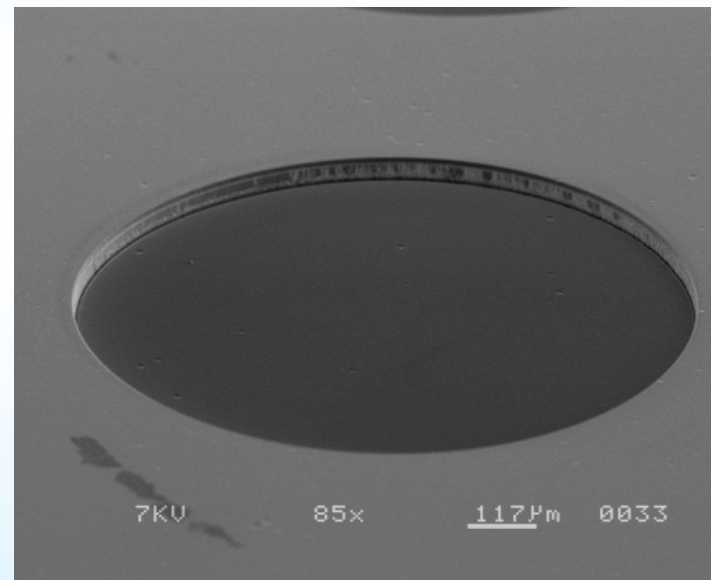
SiC is chemically inert and therefore difficult to micromachine

Micromachining methods for SiC:

- Electrochemical etching
 - developed by Kulite, early 1990's
- Deep reactive ion etching (DRIE)
 - developed by GRC, 1999



Backside of SiC diaphragm fabricated by electrochemical etching
60 µm etch depth; 1 mm diam



Backside of SiC diaphragm fabricated by DRIE
50 µm etch depth; 1 mm diam

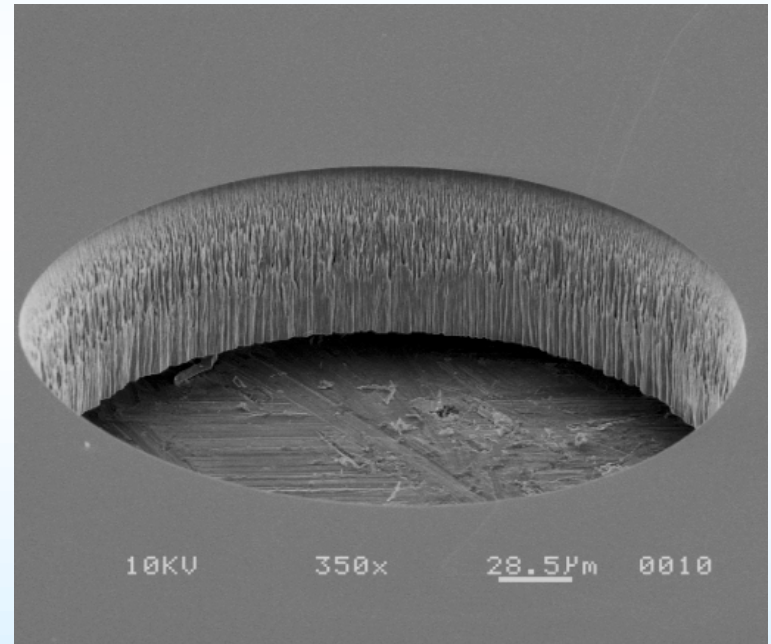
TECHNOLOGY DEVELOPMENT: SiC MICROMACHINING

Advantages of DRIE micromachining process for SiC:

- Provides vertical sidewalls, smooth etched surfaces
- Uses a durable and readily applied etch mask (nickel or indium-tin-oxide)
- High rate ($0.3\ \mu\text{m}/\text{min}$); uses automated equipment



DRIE system in GRC cleanroom

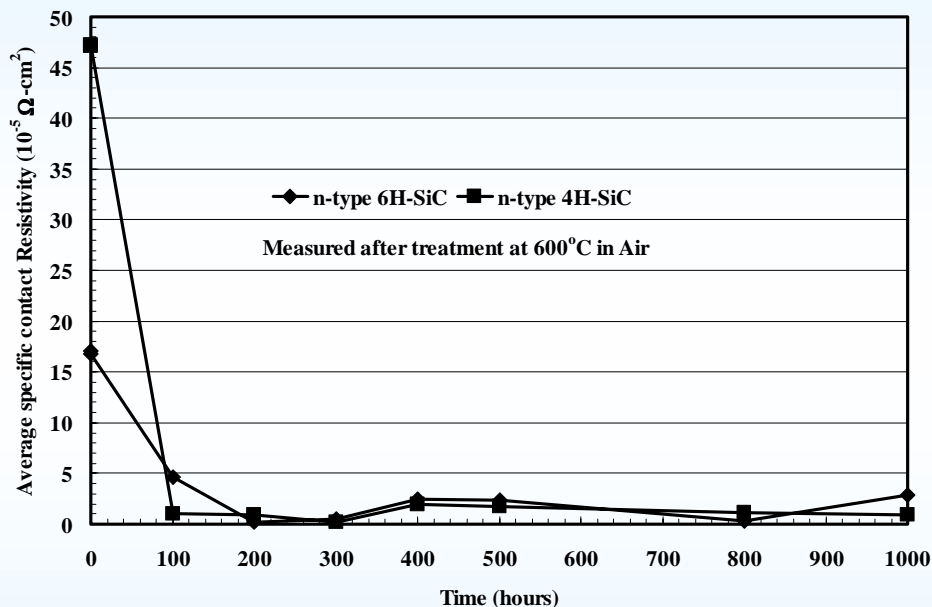


Hole etched by DRIE through a $100\ \mu\text{m}$ thick SiC wafer

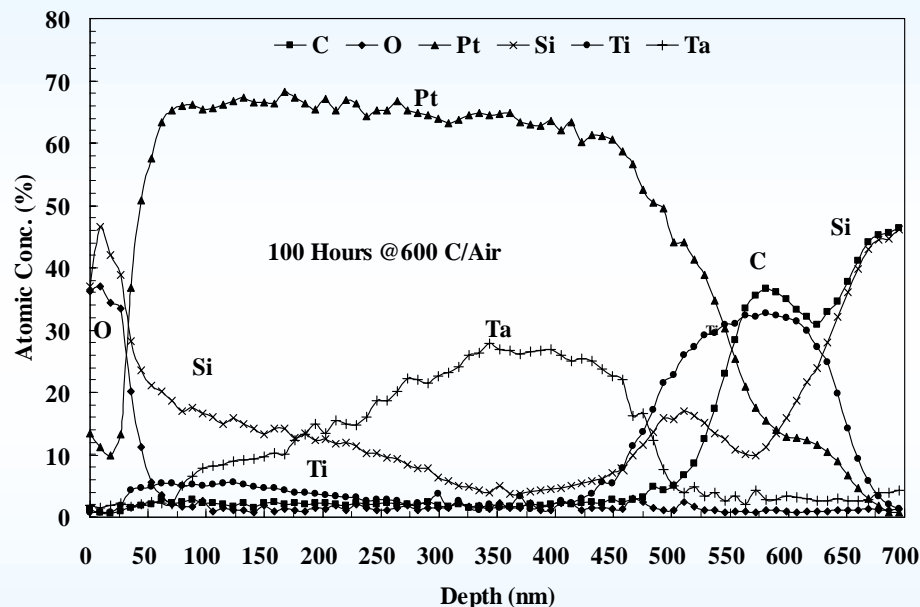
The DRIE process for SiC is an enabling technology for harsh environment MEMS

TECHNOLOGY DEVELOPMENT: HIGH TEMPERATURE CONTACTS

A three layer contact structure, titanium/tantalum silicide/platinum, has shown minimal degradation in performance after more than 1000 hrs at 600 °C

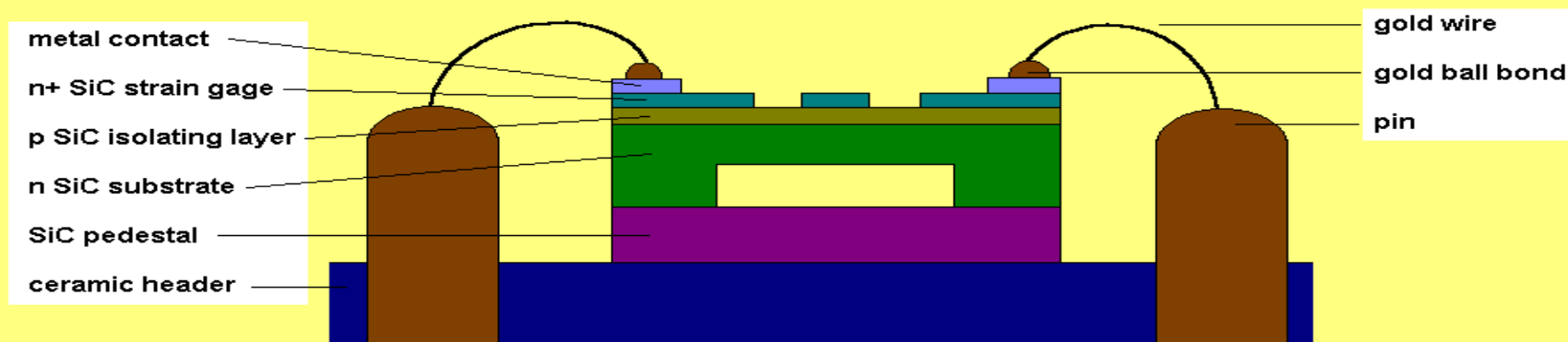


Contact resistance as a function of time exposed to 600 °C. Recently, 1000 hrs at 600 °C has been demonstrated.



Auger depth profile of contact exposed to 600 °C for 100 hrs. Following burn-in, a platinum silicide diffusion barrier is formed, which protects the underlying layers from oxidation.

TECHNOLOGY DEVELOPMENT: HIGH TEMPERATURE SiC PRESSURE SENSOR PACKAGING

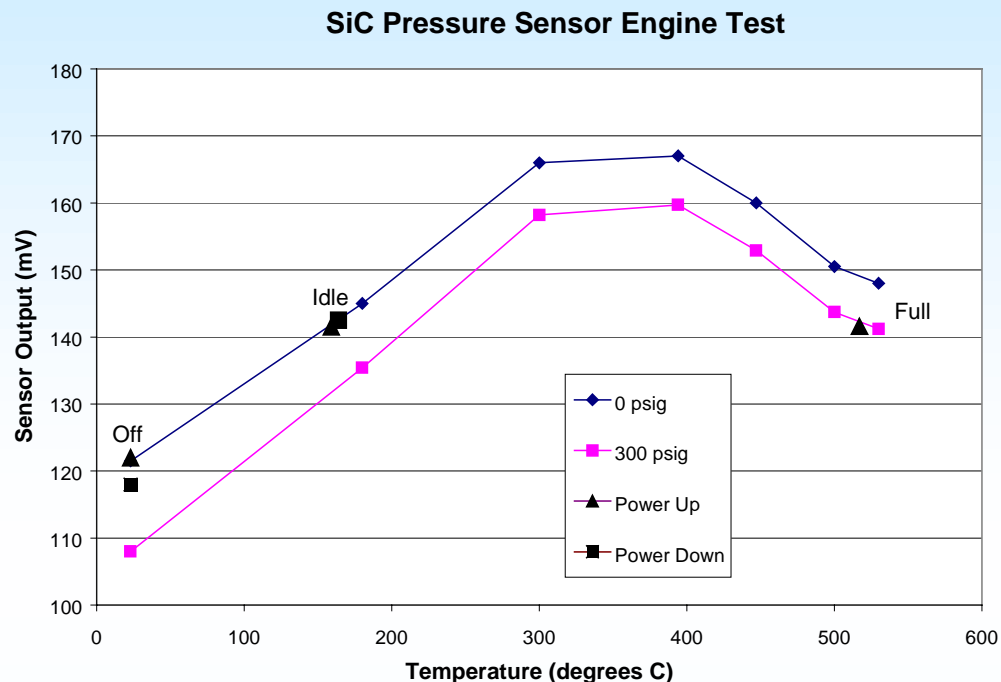
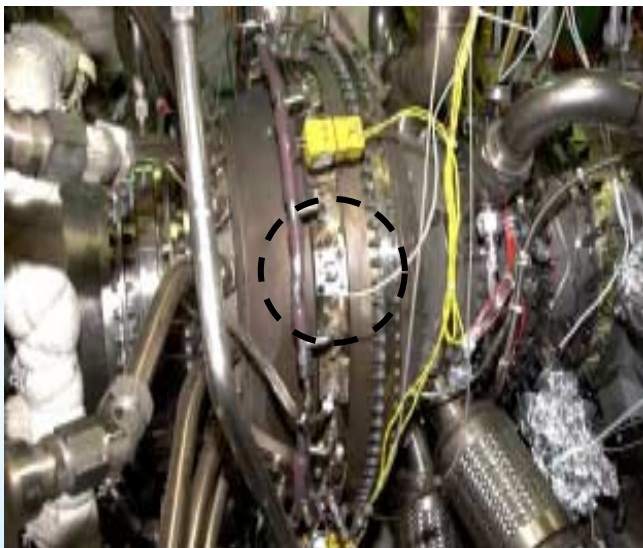


Cross section of SiC pressure sensor package

High Temperature SiC Pressure Sensor: Engine Test



Above: 500 °C SiC pressure sensor

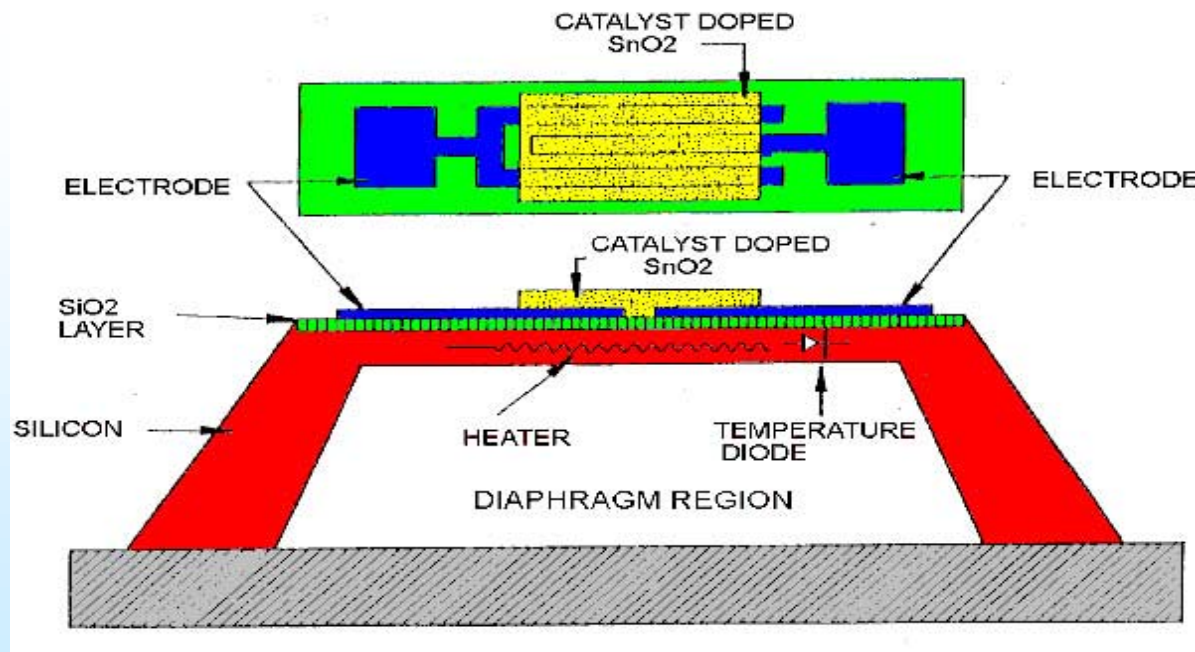


Above: data from the engine test is superimposed on calibration data for the sensor. A 4 mV output shift is produced upon exposure to the peak temperature. Further work will aim to decrease sensor drift.

Left: SiC pressure sensor installed in compressor deswirl region of Honeywell AS907 core engine.

MICROFABRICATED TIN OXIDE BASED NO_x AND CO SENSOR TECHNOLOGY

- MICROFABRICATED FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION
- MICROMACHINED TO MINIMIZE POWER CONSUMPTION AND IMPROVE RESPONSE TIME
- TEMPERATURE DETECTOR AND HEATER INCORPORATED INTO SENSOR STRUCTURE
- NANOFABRICATION OF TIN-OXIDE TO INCREASE SENSOR STABILITY



STRUCTURE OF A MICROFABRICATED TIN-OXIDE SENSOR



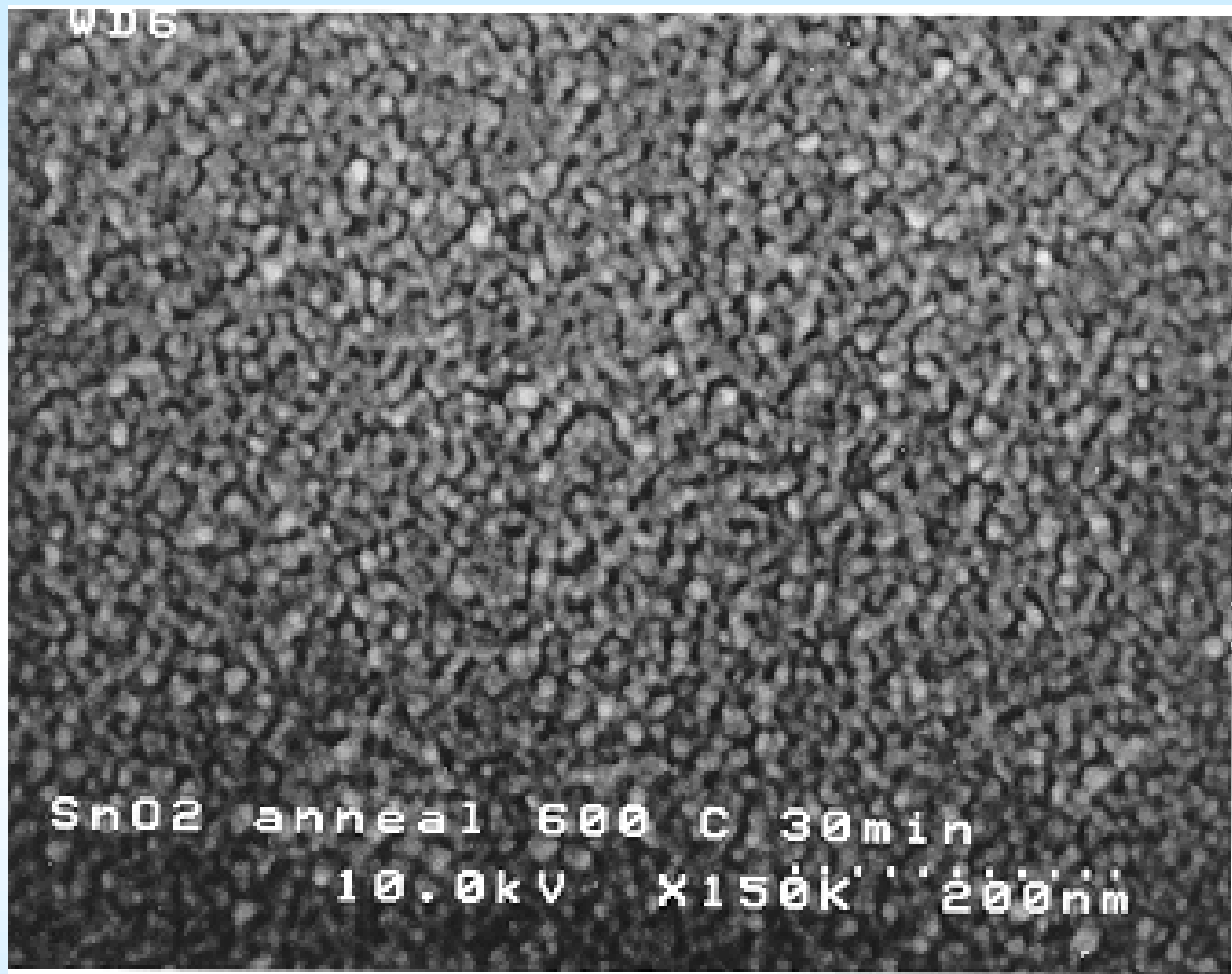
ALTERNATE PROCESSING YIELDS IMPROVED SENSOR PROPERTIES

PROPERTIES OF NANOCRYSTALLINE SnO_2 THIN FILM FROM SOL-GEL PROCESS

- **SMALL PARTICLE SIZE**
- **HIGH POROSITY**
- **LARGE SURFACE AREA**
- **HOMOGENEOUS CHEMICAL AND PHYSICAL STRUCTURE**

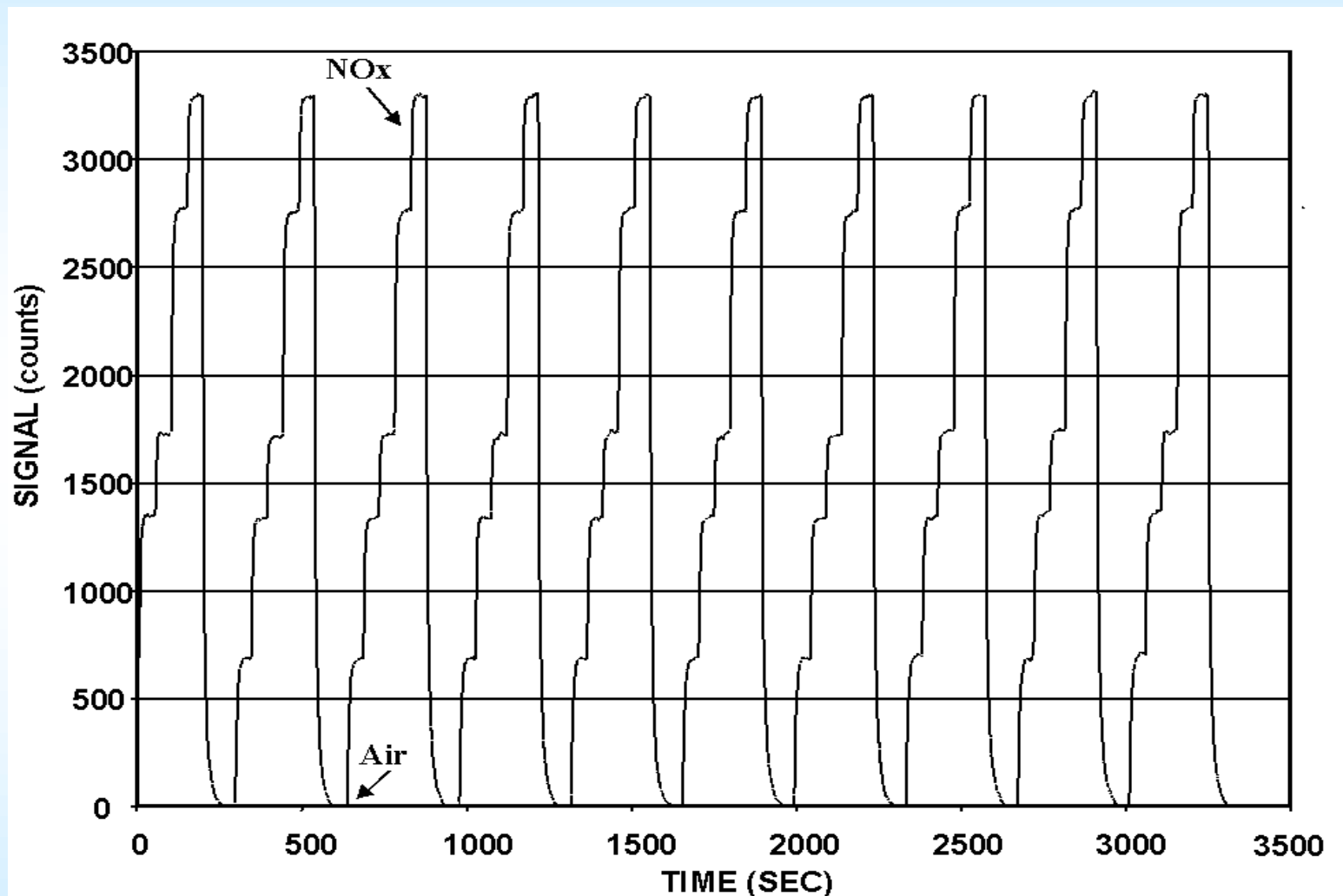
ADVANTAGES FOR SENSOR APPLICATIONS

- **HIGH SENSITIVITY**
- **FAST RESPONSE**
- **STABLE OPERATION**



Nanocrystalline SnO₂ after annealing at 600 °C for 30 minutes.

THE RESPONSE OF A DOPED SnO_2 SENSOR TO CYCLED CONCENTRATIONS OF NO_x

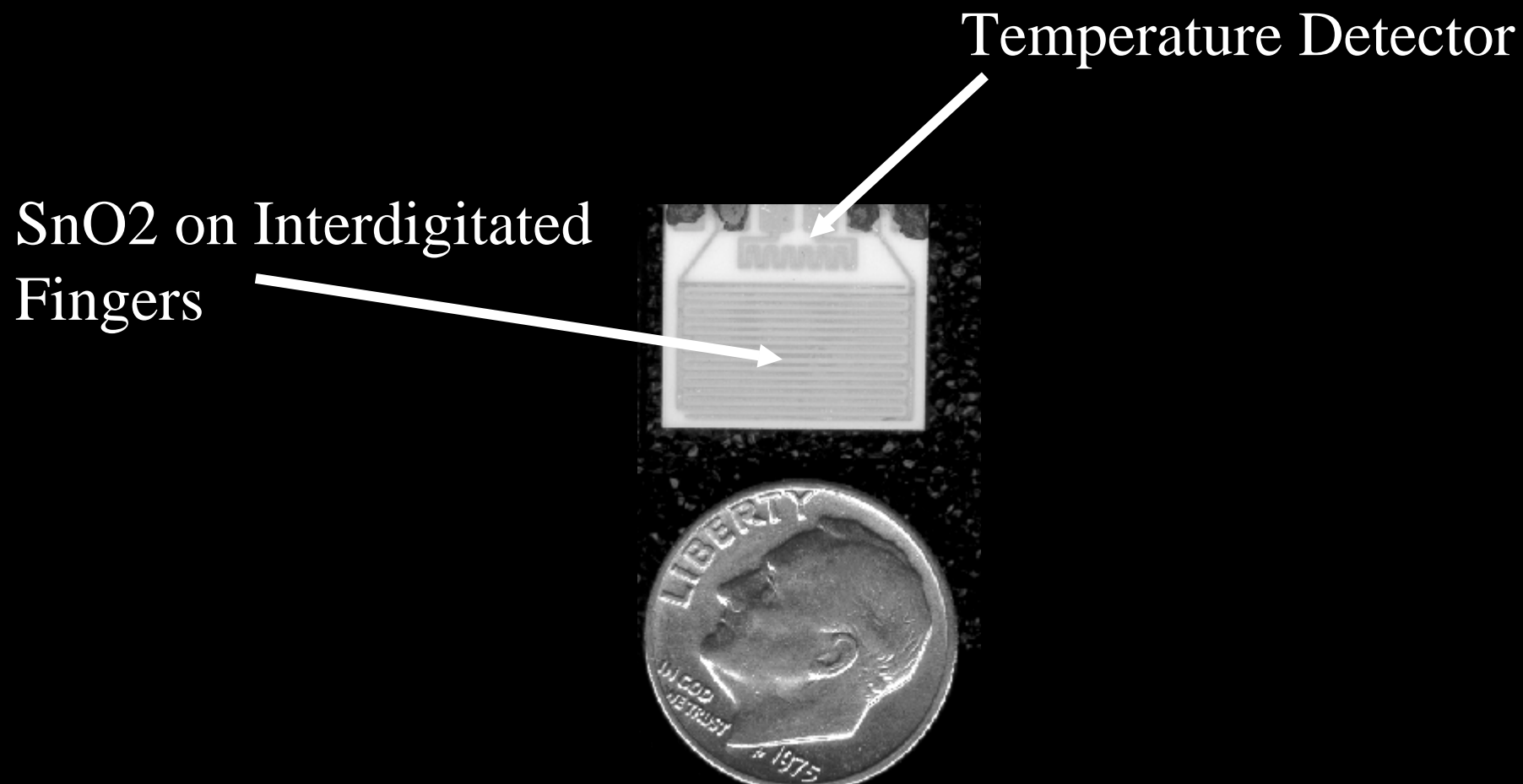


STEPS: 0 TO 3 TO 6 TO 12 TO 25 TO 50 PPM AND BACK TO 0 IN AIR

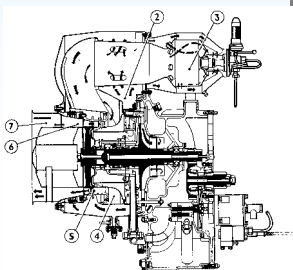
T= 350°C

PACKAGING TAILORED FOR THE APPLICATION

**SnO₂ SENSORS ON CERAMIC SUBSTRATE
RATHER THAN SILICON FOR ENGINE TESTING**

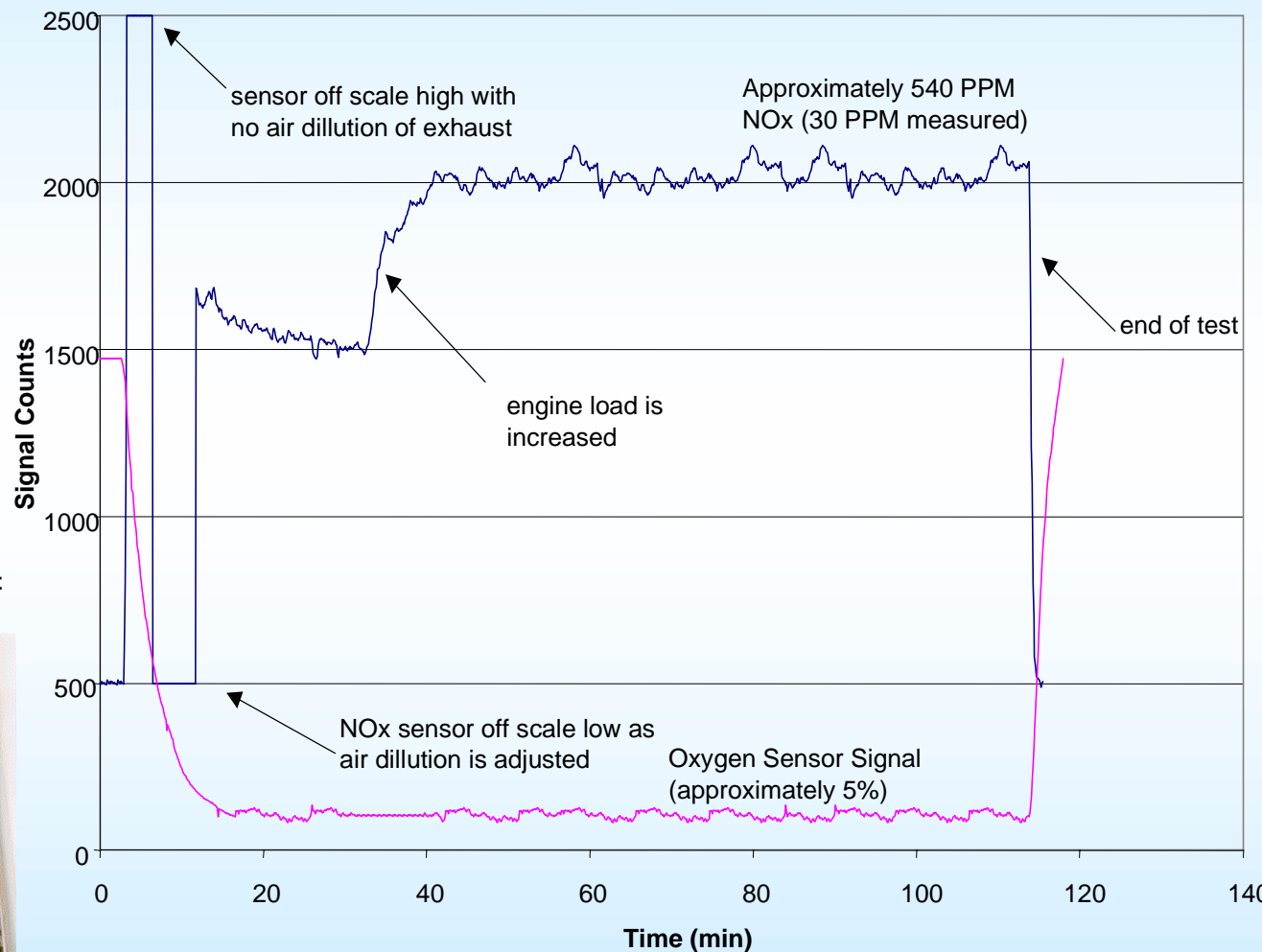
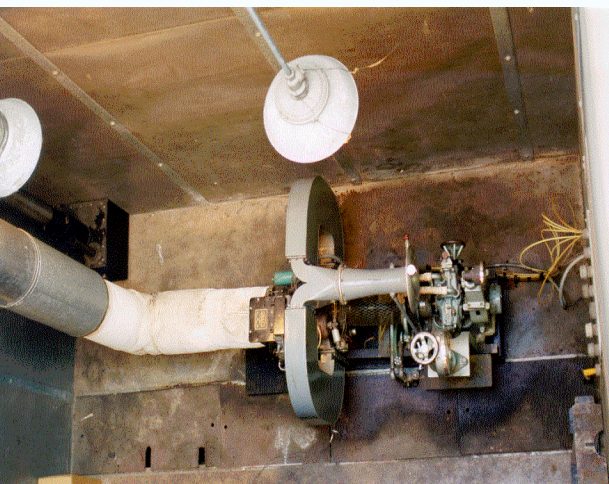


Demonstration Testing Of NO_x Sensor In Gas Turbine Exhaust Stream



50 Hp Gas Turbine

Industry Standard
Continuous Emission
Monitoring Equipment



Species	CEM Measurement	MSES Measurement
NO _x	593 PPM	540 PPM
CO	3000 PPM	N/A
O ₂	4.57%	5%

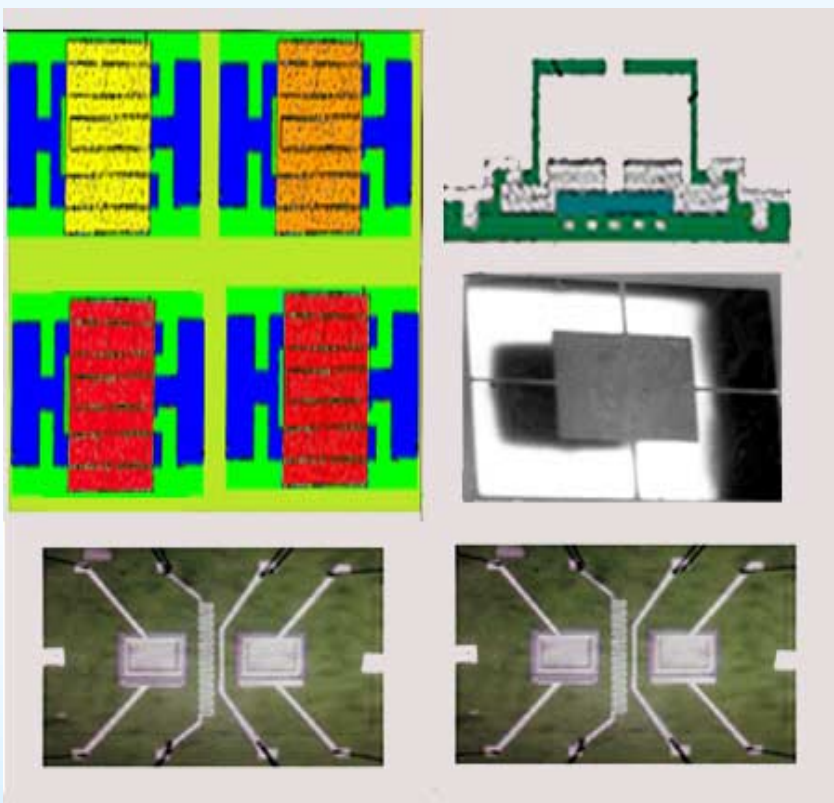
GLENNAN MICROSYSTEM INITIATIVE

MICROFABRICATED EMISSION SENSOR ARRAY CONCEPT HIGH TEMPERATURE ELECTRONIC NOSE

**SnO₂
Resistor**

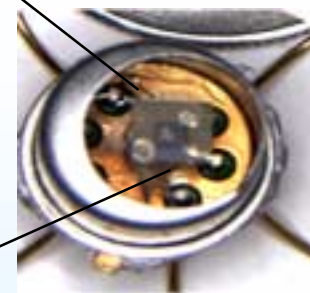
**TiO₂
Resistor**

**Electrochemical Oxygen
Sensor**



**Selectively
Filtered
SnO₂ Resistors**

**SiC-Based
Pressure Sensor**

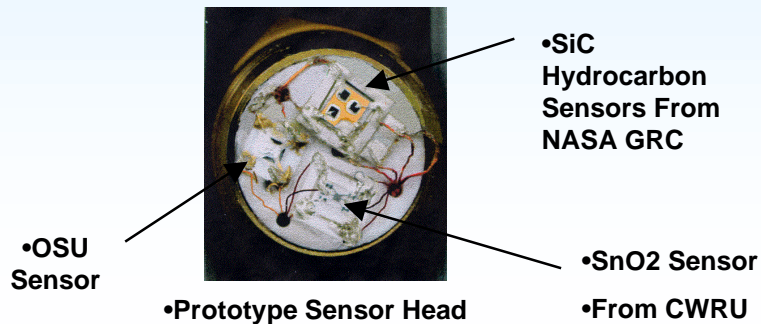


**Metal-SiC
Schottky diodes**

**Metal-Reactive Insulator
SiC Schottky diodes**

Brassboard Integrated Electronic Nose System

High Temperature Nose Requires Packaging Beyond Room Temperature Systems

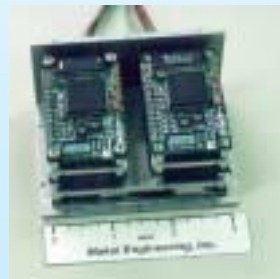


- Sensor Operating Temperature 400 C with +/- 8 C stability in dynamic environment



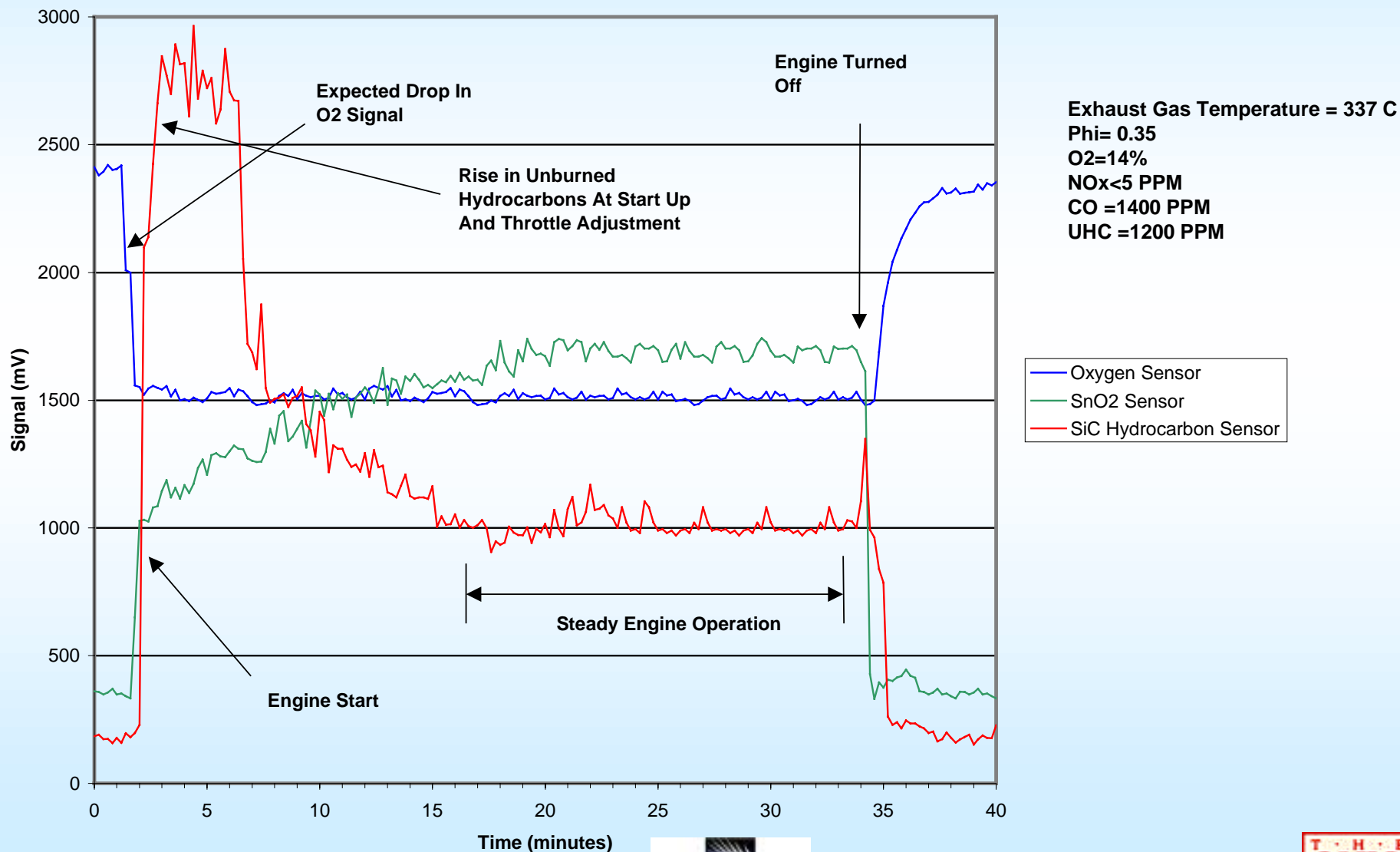
•Electronics and Sensor Head

- Sensors Tested
 - Oxygen (0 to 21%)
 - CO (0 to 3000 PPM)
 - Hydrocarbons (0 to 2500 PPM C₂H₂)
 - NO_x (0 - 300 PPM)



Harsh Environment Demonstration Testing

1.9 liter, four cylinder HCCI at U.C. Berkeley (propane/air)





SUMMARY

- **RELIABILITY IS A SIGNIFICANT ISSUE IN HIGH TEMPERATURE SENSORS AND ELECTRONICS**

**PHYSICAL AND CHEMICAL SENSORS
HIGH TEMPERATURE ELECTRONICS/SENSORS**

- **SENSOR AND ELECTRONICS DEVELOPMENT**

**TAILOR DEVICE TO APPLICATION/WHOLE SYSTEM APPROACH
MULTILAYER LAYER APPROACHES NECESSARY
NEW MATERIALS DEVELOPMENT**

- **CONNECTIONS WITH FROM DEVICE TO OUTSIDE USER A MAJOR COMPONENT OF DEVICE RELIABILITY**

**LEAD WIRES
CONTACTS
PACKAGING**

- **DEMANDS ON RELIABILITY OF INDIVIDUAL COMPONENTS WILL INCREASE WITH THE DEVELOPMENT OF INTEGRATED MICROSYSTEMS**